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THE ROLE OF CONVERGENCE IN
STEREOSCOPIC DEPTH CONSTANCY

Robert Cormack and Arthur Menendez

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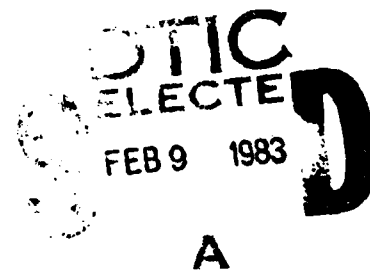Vanderbilt University
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Technical Report

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER N14-0001 83C-0001	2. GOVT ACCESSION NO. AD-A124 231	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE ROLE OF CONVERGENCE IN STEREOSCOPIC DEPTH CONSTANCY		5. TYPE OF REPORT & PERIOD COVERED TECHNICAL
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) ROBERT CORMACK AND ARTHUR MENENDEZ		8. CONTRACT OR GRANT NUMBER(s) N00014-81-C-0001
9. PERFORMING ORGANIZATION NAME AND ADDRESS VANDERBILT UNIVERSITY NASHVILLE, TENNESSEE 37240		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N 42; RR04209; RR0420902; NR 197-067
11. CONTROLLING OFFICE NAME AND ADDRESS ENGINEERING PSYCHOLOGY PROGRAMS, ONR 800 NORTH QUINCY STREET, CODE 455 ARLINGTON, VIRGINIA 22217		12. REPORT DATE JANUARY 1983
		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) VANDERBILT UNIVERSITY NASHVILLE, TENNESSEE 37240		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Stereopsis	Afterimages
Depth	Convergence
Depth constancy	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In order for retinal disparity to be used in making veridical depth judgments, stereoscopic depth constancy must occur. That is, retinal disparity must be rescaled as a function of fixation distance. This is necessary because the retinal disparity associated with a given depth interval varies with the overall distance of the depth interval from the

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observer. Since accurate depth judgments based on retinal disparity can be made over a wide range, such a rescaling must be made. For both theoretical and practical reasons, it is of importance to know the source of information used by the visual system to recalibrate retinal disparity as fixation distance changes.

The present study assessed the importance of convergence in the rescaling of retinal disparity. Observers made depth judgments under three conditions of convergence: normal viewing, 5 diopters of forced convergence, and 25 diopters of forced convergence. An afterimage technique was used to produce a target in depth with approximately 16 minutes of crossed retinal disparity independent of viewing distance. Depth judgments were made at distances of 5, 10, and 20 meters in an environment rich in cues to fixation distance.

The results showed no consistant effects of 5 diopters of convergence and only marginal effects of 25 diopters of convergence. These findings show that convergence cannot be the sole source of distance information for rescaling retinal disparity. They suggest that, in the presence of other sources of distance information, convergence plays a minor role in stereoscopic depth constancy. Finally, these data demonstrate the usefulness of the stereoscopic afterimage technique in addressing problems relating to stereoscopic depth perception.

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THE ROLE OF CONVERGENCE IN
STEREOSCOPIC DEPTH CONSTANCY

In sensing the distance to a target or in judging the depth interval
between two targets, the observer relies on several sources of information.
These sources are referred to as depth or distance cues. For most observers,
an important depth cue arises from the fact that the two eyes view the world
from different locations. As a result, the images in the two eyes are
slightly different. If the scene viewed by the two eyes is flat and perpen-
dicular to the line of sight, as with a photograph or painting, then the
differences in the images will be vanishingly small. On the other hand, if
some objects in the visual field are closer than others, then the relative
locations of the images of these objects will differ in the two eyes. Fig-
ure 1 illustrates this effect.

The difference in the relative locations of images in the two eyes is
termed retinal disparity and carries information about the relative locations
of the objects in three dimensional space. This information, however, is
ambiguous. A given retinal disparity will reflect different depth intervals
depending on a number of factors. Two factors are of special importance here.
One is the interpupillary distance (i.e., the distance between the two eyes).
The other is the absolute distance of one or the other object. Interpupillary
distances are constant (or nearly so) for a given observer. But the absolute
distance of the objects can, and does, vary over a wide range.

As the absolute distance from the observer to the fixated object (here-
after called the fixation distance) increases, so does the depth interval
required to produce a given retinal disparity. The relationship among fixa-
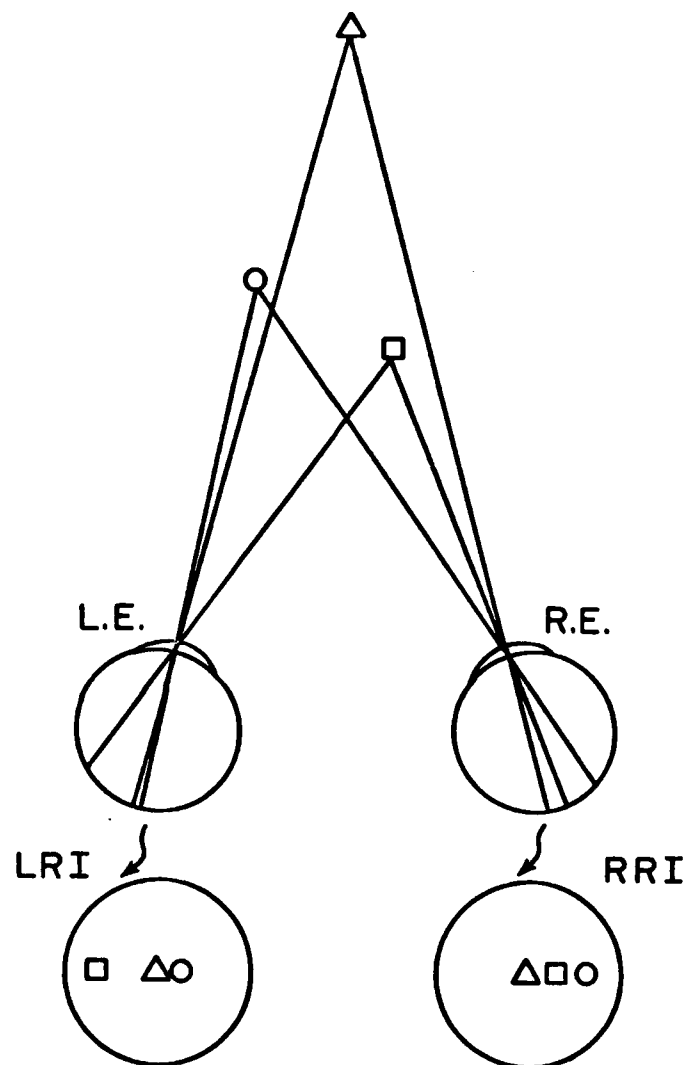tion distance, depth, and disparity is given by the equation:

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Figure 1. Differences in the images in the two eyes for three
targets (triangle, circle, and square) at different
distances. LE – left eye; RE – right eye; LRI – left
retinal image; RRI right retinal image.

1) d=D-(.5P(TAN(ATN(D/.5P)-.5R)))

where d = depth interval, P = interpupillary distance, D = fixation dis-
tance, and R = retinal disparity. This equation holds when fixation is
nearly straight ahead and the targets in depth are within a few degrees of
fixation. The derivation of this equation is given in the Appendix.

Figure 2 shows the resulting depth intervals when Equation 1 is applied
to a range of fixation distances for several different retinal disparities.
The graph can be interpreted in either of two ways. By the first interpre-
tation, it shows the depth interval required to produce the indicated reti-
nal disparity for a given fixation distance. In this case, the interpreta-
tion is simply a statement concerning the geometry of retinal disparity.

A second interpretation is concerned instead with the perception of
depth. This interpretation assumes that depth perception mediated by reti-
nal disparity is veridical, or nearly so. If such is the case, then each
curve in Figure 2 can be interpreted as showing how perceived depth changes
as fixation distance varies, while retinal disparity remains constant.
Each curve shows that as fixation distance increases the apparent depth pro-
duced by a given disparity also increases. At short fixation distances,
the depth interval increases rapidly with fixation distance, approaching a
squared relationship. At greater fixation distances, the increase is more
modest, approaching a linear relationship. Another way of viewing this is
to pick a given depth in Figure 2 and to note that each curve crosses that
depth interval at a different fixation distance. Thus, as fixation distance
changes, the disparity required to signal a given depth interval also
changes.

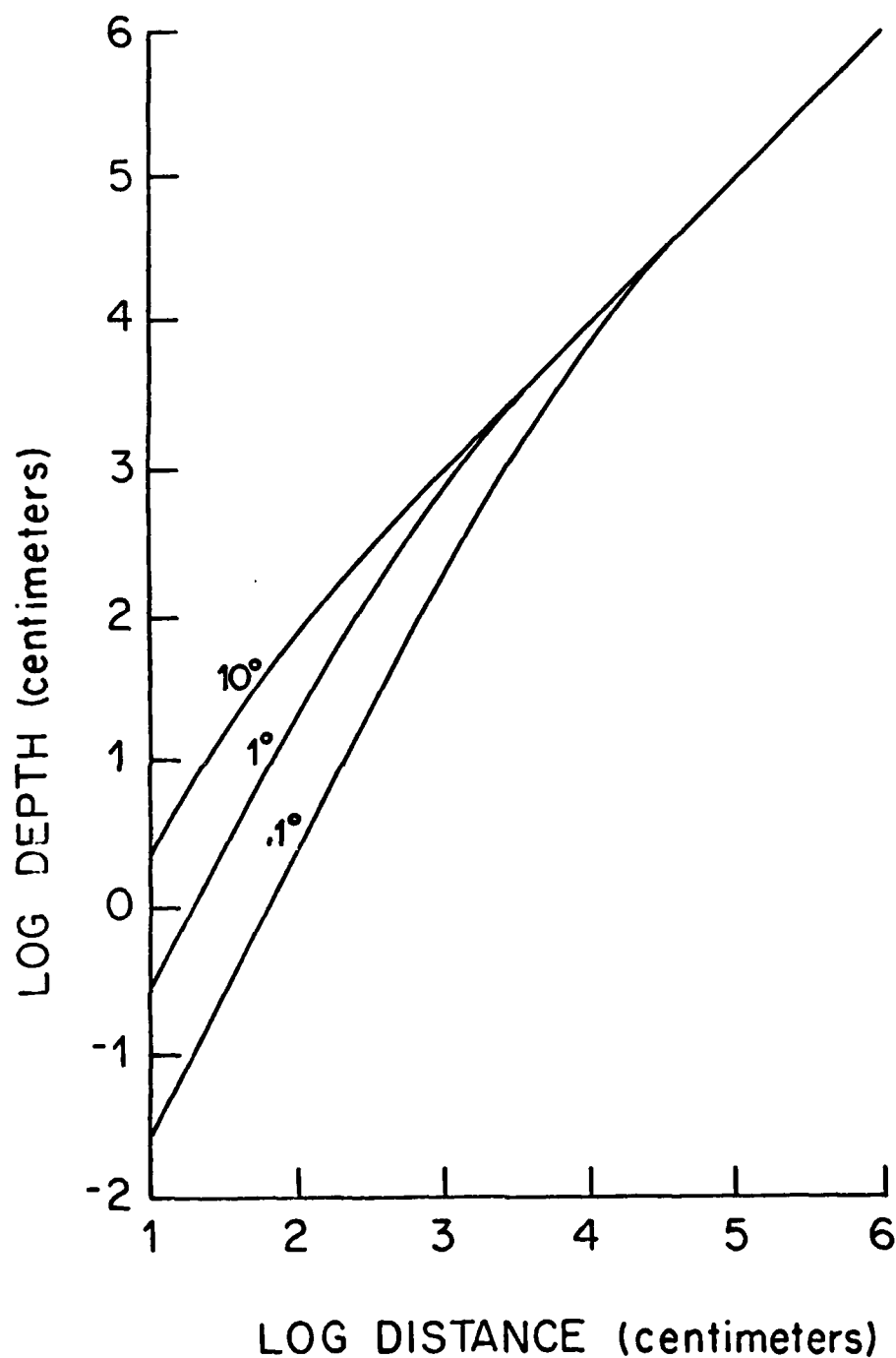This view may be seen more clearly in Figure 3. Here is illustrated

Figure 2. Depth interval required to produce .1, 1, and 10 degrees
of retinal disparity as a function of fixation distance.
Each line represents the indicated retinal disparity in
degrees. Distance and depth are in log centimeters.
Interpupillary distance is assumed to be 6.5 cm.

the same geometry as given in Equation 1, but recast to solve for retinal disparity. Each curve in Figure 3 shows the retinal disparity required to produce a given depth interval as fixation distance changes. Again, if depth perception signalled by retinal disparity is veridical, then Figure 3 shows that the same apparent depth interval may be produced by different retinal disparities, depending on fixation distance.

It is, of course, an empirical question whether or not depth perception mediated solely by retinal disparity is veridical. If it is, then the visual system must somehow solve or at least approximate Equation 1. That is, the visual system must rescale retinal disparity as a function of fixation distance to obtain accurate apparent depth. The quest to discover whether such rescaling does take place has occupied a central position in the study of depth constancy.

Depth constancy is a specific instance of the general problem of perceptual constancy. Perceptual constancy simply refers to the fact that certain aspects of our phenomenal world remain stable or constant in the face of great changes in the patterns of stimulation arriving at our sense organs. As objects approach us, the images they produce on the retina grow. Generally, the object is not perceived as enlarging but rather as coming nearer. This tendency to perceive size as stable while image size changes is termed size constancy. Similarly, any tendency for perceived depth intervals to remain constant as retinal disparity changes is termed depth constancy.

The results of a number of studies demonstrate that depth constancy occurs (e.g., Wallach & Zuckerman, 1963; Foley, 1980; Cormack, 1982a,b). Ono and Comerford (1977) have reviewed many of these studies and conclude that depth constancy certainly occurs at short fixation distances (<2 meters),
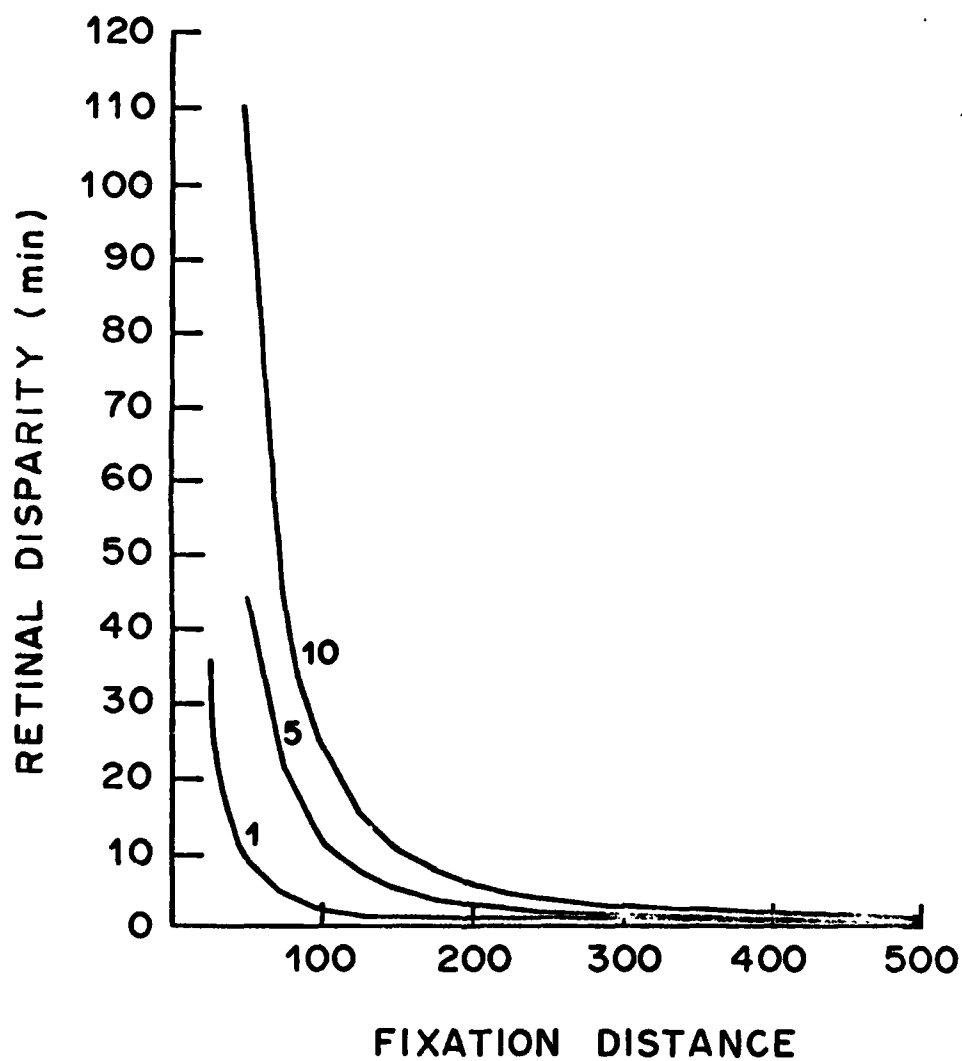
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Figure 3. Retinal disparity (min of angle) required to produce a specific depth interval as a function of fixation distance. The three curves represent 1, 5, and 10 cm of depth. Fixation distance is in centimeters. Interpupillary distance is assumed to be 6.5 cm.

but is doubtful at larger fixation distances. Cormack's (1982a,b) data suggest that depth constancy holds for any and all fixation distances.

Attention to Equation 1 reveals that in order for depth constancy to occur when depth is signalled by retinal disparity, the visual system must have information concerning fixation distance. Fixation distance must be known to solve for depth interval. In most situations in everyday life, many sources of information about fixation distance are available. These include, among others, perspective, texture gradients, familiar size, motion parallax, and oculomotor cues. It is of interest to know which cues can be or are used to rescale retinal disparity as a function of fixation distance.

The fact that demonstrations of distance constancy are more abundant for short fixation distances has caused particular attention to be paid to those cues which operate in this range. Oculomotor cues such as accommodation and convergence would appear to be likely candidates. One factor that makes them appealing is that unlike most cues to distance, these cues are, at least in theory, capable of providing absolute distance information. Most other distance cues provide only relative distance information and require other data to yield an absolute metric. While it is known that accommodation is a relatively weak distance cue, that is certainly not the case with convergence.

These considerations suggest that convergence might occupy a pre-eminent, if not sole, role in the rescaling of retinal disparity. Although the discovery of depth constancy at large fixation distances (Cormack, 1982a,b) might weaken this conclusion, it does not contradict it.

The present study was conducted to investigate directly the effect of convergence on depth constancy under conditions where retinal disparity provided the only information about the depth intervals to be judged.

METHOD

Subjects

Three males served as observers. Each observer had 20/20 visual acuity or wore their correction to 20/20 throughout the experiment. All observers scored within normal limits for stereo-acuity, as measured on the Orthorater, and all correctly identified figures seen in depth in Julesz random element stereograms (Julesz, 1971). One observer was naive as to the purpose of the experiment and was unaware of the geometry of retinal disparity. The other two observers were both experienced psychophysical observers.

Apparatus

Figure 4 shows the apparatus used to generate afterimages. It is designed to produce a stereoscopic afterimage with specific retinal disparity by flashing an intense light through a stimulus possessing contours at different depths. It has been described in detail elsewhere (Cormack, 1982b). Briefly, it is a hand held portable device with a forehead rest to maintain a constant fixation distance. Eye ports afford a view of a stimulus with depth constructed from a "sandwich" of opaque and translucent materials. The stimulus pattern produced by this "sandwich" is shown in Figure 5. Fixation bars are visible in an horizontal aperture bisecting the target. The circular apertures in the otherwise opaque masking material are .93 cm in front of the fixation bars. The fixation bars are located 35 cm from the observer's eyes. This puts the circular apertures at approximately 16.3 min of crossed retinal disparity (the exact disparity depending on the specific interpupillary distance of the observer). The diffusing screen and photographic flash gun are located behind the stimulus slides. The

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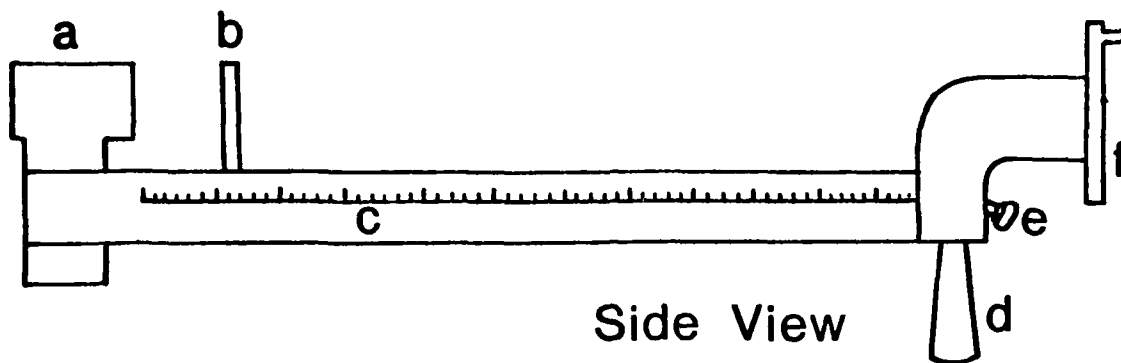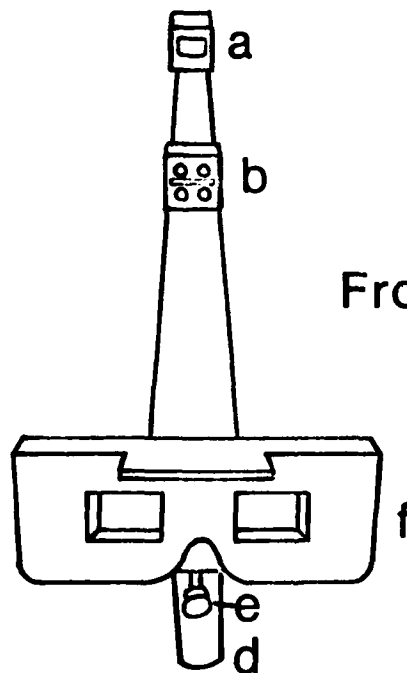
Figure 4. Apparatus used to produce stereoscopic afterimages.
a – flashgun; b – target "sandwich"; c – scale; d – handle;
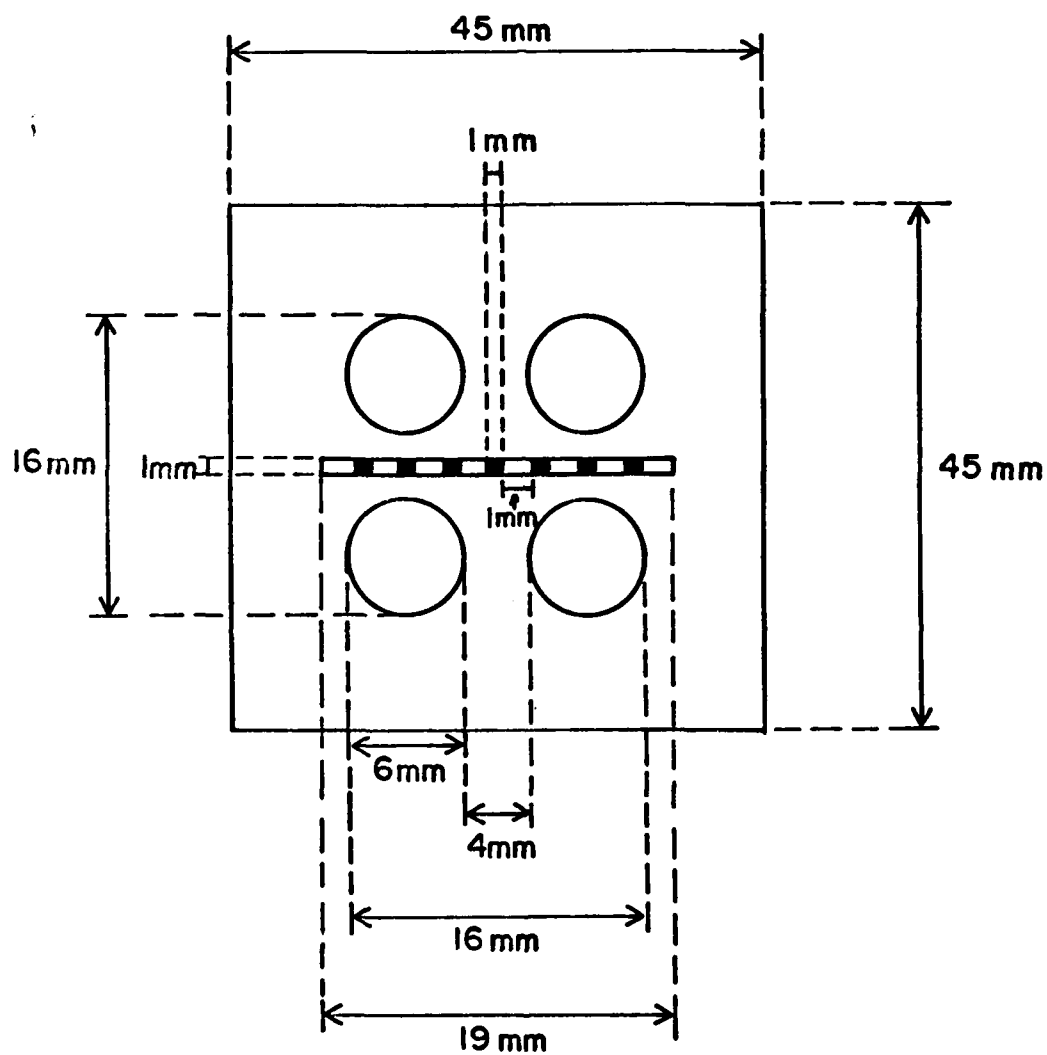e – pushbutton; f – viewing ports and forehead rest.

Figure 5. Stimulus pattern produced by target "sandwich." Circles and horizontal dashed bar are translucent. Background is opaque. Circles stand out in depth from the horizontal bar.

flash gun is at a distance of 60 cm from the observer's eyes and is trig-
gered by depressing, with the thumb, a switch located just below the handle.

The experiment was conducted in a long hallway with a screen placed at
one end. The arrangement is shown in Figure 6. A strobe light flickering
at approximately 4 hz was used to illuminate the screen and served to main-
tain a vivid afterimage. A fixation target consisting of a rod (30 cm tall
by 4 cm wide) was mounted at eye level on a tripod which was 85 cm in front
of the screen. This fixation stimulus and various potential distance cues
(e.g., doorways, tiles, cement blocks, etc.) were clearly visible even
though, except for the strobe, the hallway was dimly illuminated.

Procedure

For all trials, the induction of an afterimage was identical. After
dark adapting for several minutes, the observer held the afterimage genera-
tor to the eyes and fixated carefully on the fixation point in the slides
(the vertical bar in the center of the horizontal aperture). When good
fixation was achieved, the observer triggered the flash gun. For the forced
convergence conditions, the observer next donned trial frames fitted with a
pair of symmetrically set base out variable prisms. The observer then fix-
ated the fixation stimulus located at the end of the hall. Total prismatic
deviations of 5 and 25 prism diopters were employed for the "weak" and
"strong" forced convergence conditions, respectively, and produced total
angular deviations of 2.9 and 14.3 degrees corresponding to undeviated
convergence distances of 130 and 26 cm. A third session served as a control
condition and involved viewing the hall and fixation stimulus without prisms
but under otherwise comparable stimulus conditions. With the prisms, it
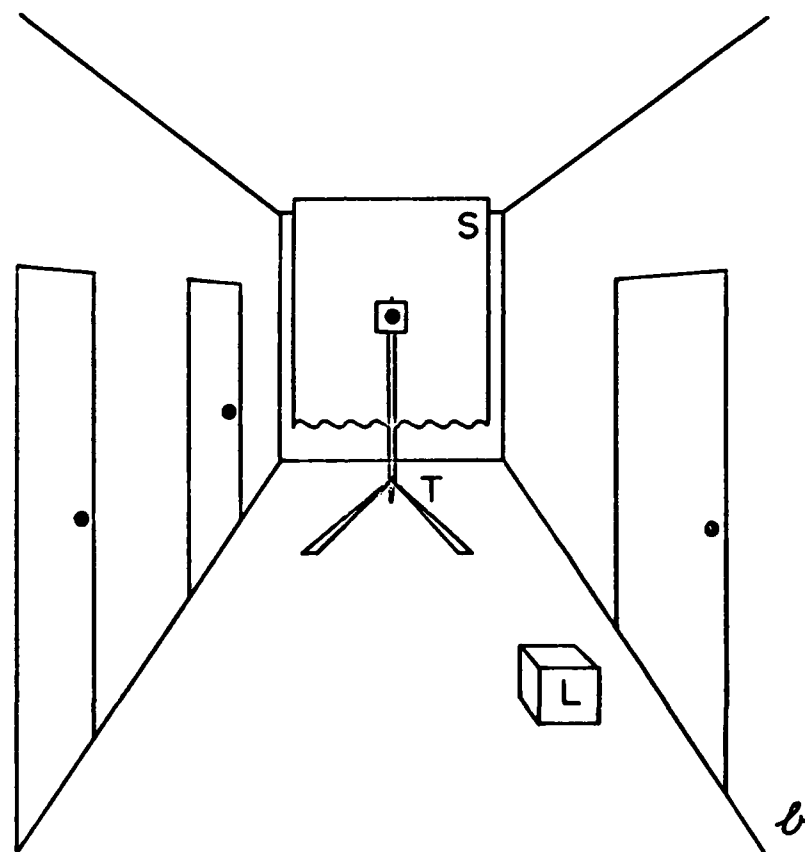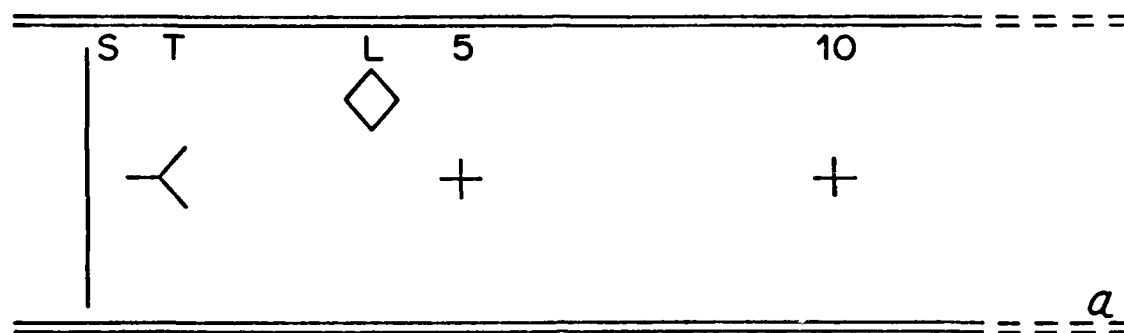was necessary for the observers to increase their convergence, relative to

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Figure 6. Experimental arrangement. a - floorplan of hallway; b - observer's view of same hallway; S - screen; T - tripod with fixation target; L - strobe light. Numbers in 6a show where observer stood for 5 and 10 meter fixation distances. Twenty meter fixation distance is off the figure.

the amount prevailing for normal viewing, in order to maintain a single image of the fixation stimulus. Observers were instructed to abort a trial if: a clear afterimage was not obtained, the afterimage of the fixation point did not appear in the fronto-parallel plane of the hallway fixation stimulus, or the fixation stimulus was seen as double.

Individual experimental sessions were conducted for each of the three convergence conditions for each observer. Within each session, three methods were employed to measure apparent depth in the afterimages. These methods are called the "probe," "percent," and "foot-estimate" techniques. They give highly correlated results and have been discussed in detail elsewhere (Cormack, 1982b).

For the probe technique, the observer fixated the fixation stimulus in the hall, while the experimenter held a six foot vertical rod (or "probe") at a randomly selected distance from the observer and immediately lateral to the afterimage. Then, as directed by the observer, the experimenter moved the probe nearer or farther until the observer reported that it appeared at the same distance as the afterimage. The distance from the fixation point to the rod, as measured with a tape measure, served as an index of apparent depth.

For the percent technique, the observer was told to consider the distance to the fixation stimulus as 100 and to express the apparent distance to the afterimage (from oneself) as a percentage of the fixation distance. Thus, if the afterimage appeared to be 1/4 of the way from the observer to the fixation point, then the observer would say 25 percent. If the afterimages of the circles appeared more than half way to the fixation point, say 3/4 of the way, then the response would be 75 percent. If no depth

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appeared in the afterimage array, then the observer would report a value
of 100 percent.

With the foot-estimate method, the observer estimated the apparent dis-
tance in feet from himself to the circles of the afterimage.

Probe, percent, and foot-estimate measures were obtained with and with-
out prisms at fixation distances of 20, 10, and 5 meters. Convergence con-
ditions were varied across sessions. Observation distance and measurement
technique were randomized across trials within a session. There were eight
trials per method per observation distance for each convergence condition
for each of the observers. Intertrial intervals were at least 2 minutes
and, in every case, were sufficient to allow the previous trial's afterimage
to fade to invisibility.

Finally, observers were asked to judge the apparent distance, in feet,
to the fixation stimulus. This was done without prisms and with the strong
(25 diopter) forced convergence. No afterimages were present during trials.
This condition served to test the hypothesis that a change in convergence
would change the apparent distance to the fixation point.

RESULTS

All results are given as the depth perceived in the afterimage in meters.
For the probe technique, the perceived depth in the afterimage was determined
by measuring directly the distance from the probe to the fixation target in
meters.

In the foot-estimate technique, the observer reported how far away the
circles in depth appeared. That is, the observer gave a judgment of egocen-
tric distance (in feet) from the observer to the circles in depth. This

egocentric distance was converted to meters and then subtracted from the total distance from the observer to the fixation point. This yielded a measure of perceived depth in the afterimage.

For the percent technique, the observer was asked to state the percent of the fixation distance represented by the egocentric distance to the afterimage circles. Thus, the greater the depth perceived in the afterimage, the smaller the percent reported by the subject. To convert the observer's report to meters of depth, the percent report was subtracted from 100 and this value multiplied by the fixation distance giving an estimate of perceived depth in meters.

A comparison of the three methods for measuring depth in the afterimages is shown in Figure 7. The histograms are presented in three blocks of nine bars, each block representing a different fixation distance (5, 10, and 20 meters). Within each block, the nine bars are further grouped according to diopters of convergence (0, 5, and 25 diopters). The vertical axis represents perceived depth in the afterimage in meters. If, for each distance, the difference between the largest and smallest perceived depth is divided by the fixation distance, and these values converted to percents, the results are 13.6, 13.7, and 13.0 for 5, 10, and 20 meters, respectively. Thus the variability among measurement methods increases roughly linearly with fixation distance.

The main effects for this study are presented in Figures 8, 9, and 10. Each figure gives data from a different measurement method. The abcissa represents fixation distance in meters. The ordinate represents perceived depth converted to meter equivalents, as described above. Each graph gives values for 0, 5, and 25 diopters as indicated by the key presented in the
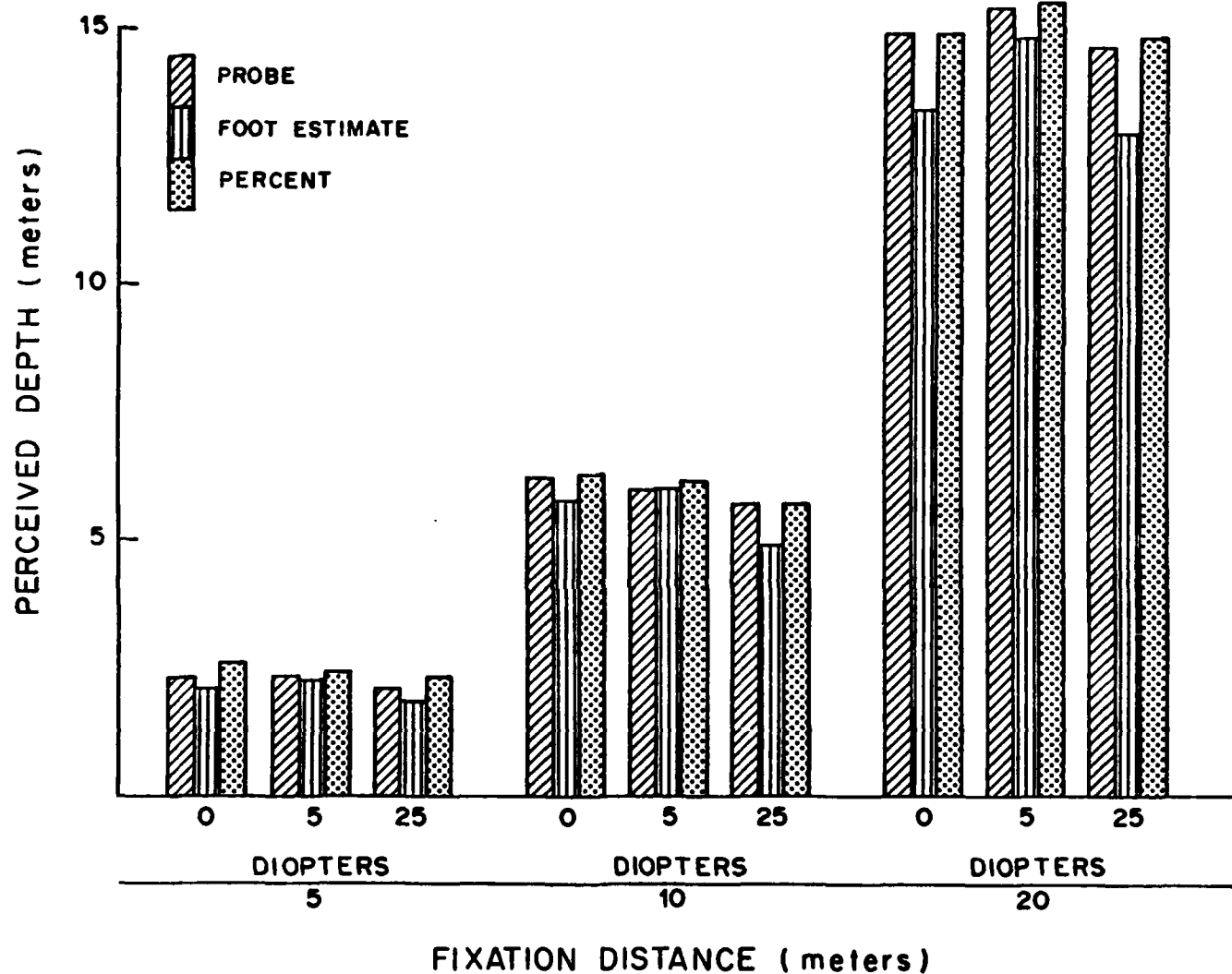
Figure 7. Comparison of Probe, Foot-estimate, and Percent techniques
for measuring the apparent depth in stereoscopic afterimages.
Each block of three histogram bars provides a comparison of
the three methods for a particular forced convergence (0, 5,
or 25 prism diopters) at a specific fixation distance
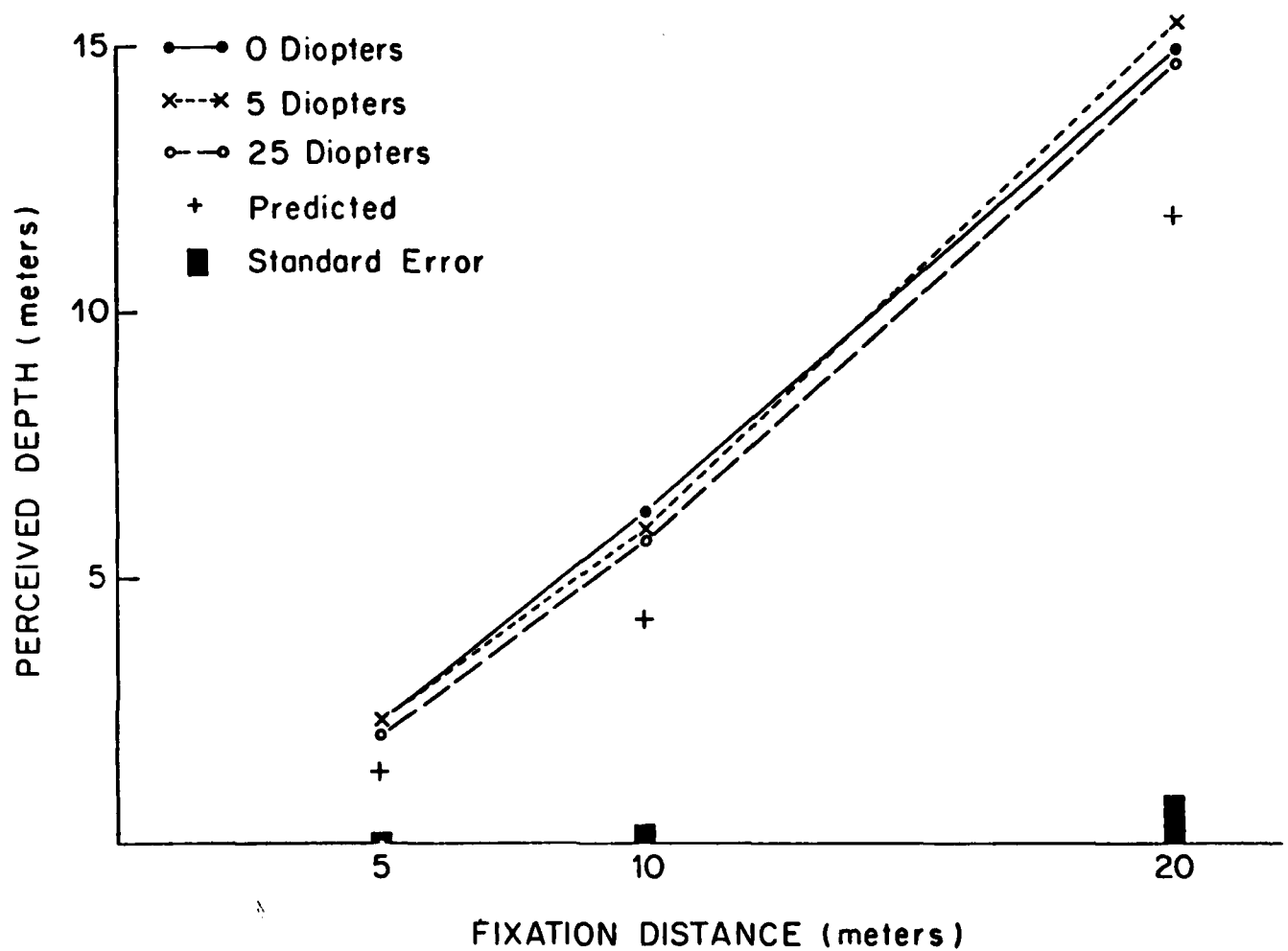(5, 10, or 20 meters).

Figure 8. Comparison of three convergence conditions (0, 5, or 25 prism diopters) using the "probe" technique. Each curve gives the apparent depth as a function of fixation distance for one convergence value. The unconnected crosses give depth values predicted by the geometry of retinal disparity. The histogram bars along the bottom give the largest standard error for any observer and for any convergence at the fixation distance specified.
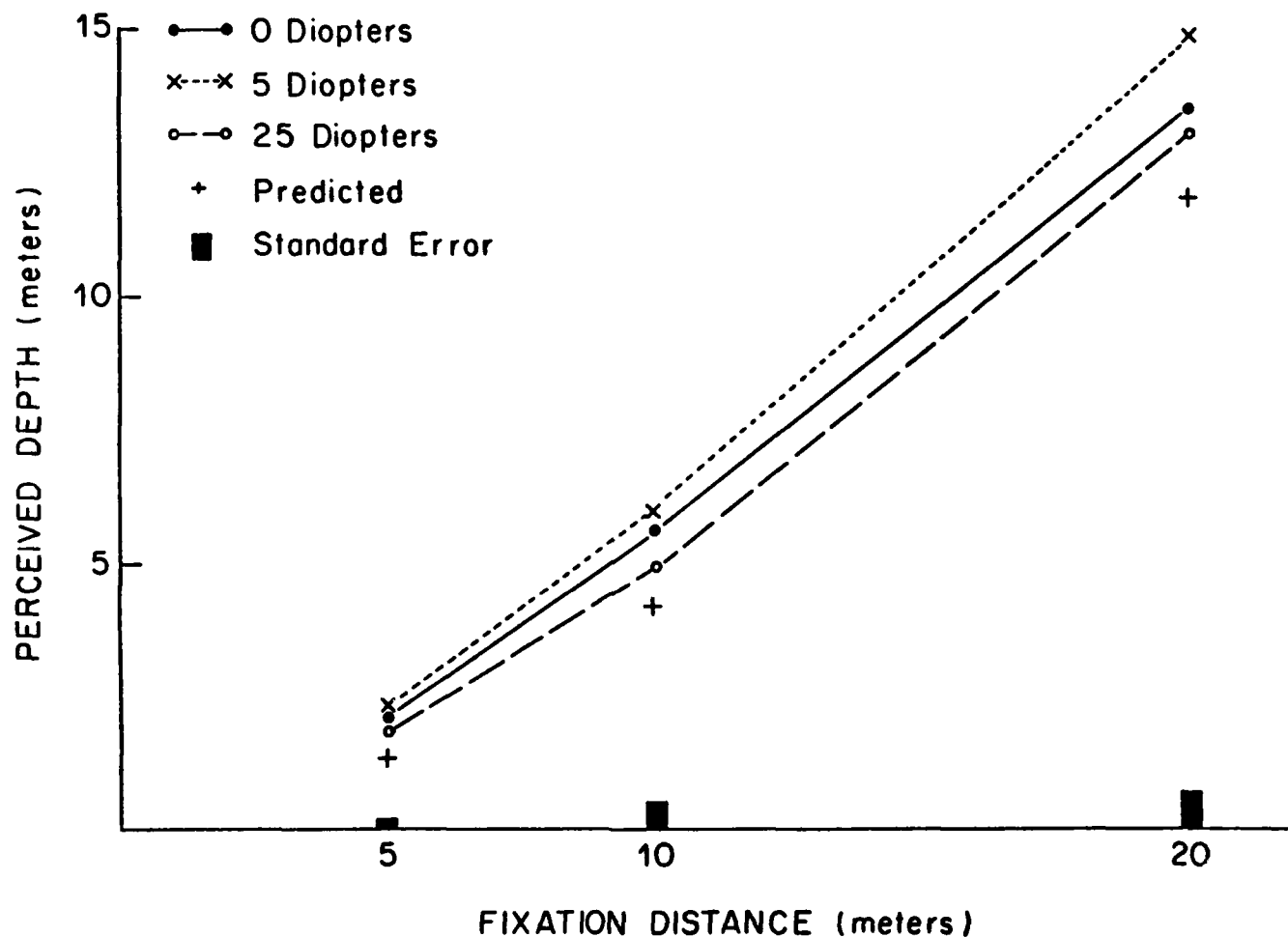
Figure 9. Comparison of three convergence conditions (0, 5, or 25 prism
         diopters) using the "foot-estimate" technique. Each curve gives
         the apparent depth as a function of fixation distance for one
         convergence value. The unconnected crosses give depth values
         predicted by the geometry of retinal disparity. The histogram
         bars along the bottom give the largest standard error for any
         observer and for any convergence at the fixation distance
         specified.

Figure 10. Comparison of three convergence conditions (0, 5, or 25 prism diopters) using the "percent" technique. Each curve gives the apparent depth as a function of fixation distance for one convergence value. The unconnected crosses give depth valued predicted by the geometry of retinal disparity. The histogram bars along the bottom give the lartest standard error for any observer and for any convergence at the fixation distance specified.
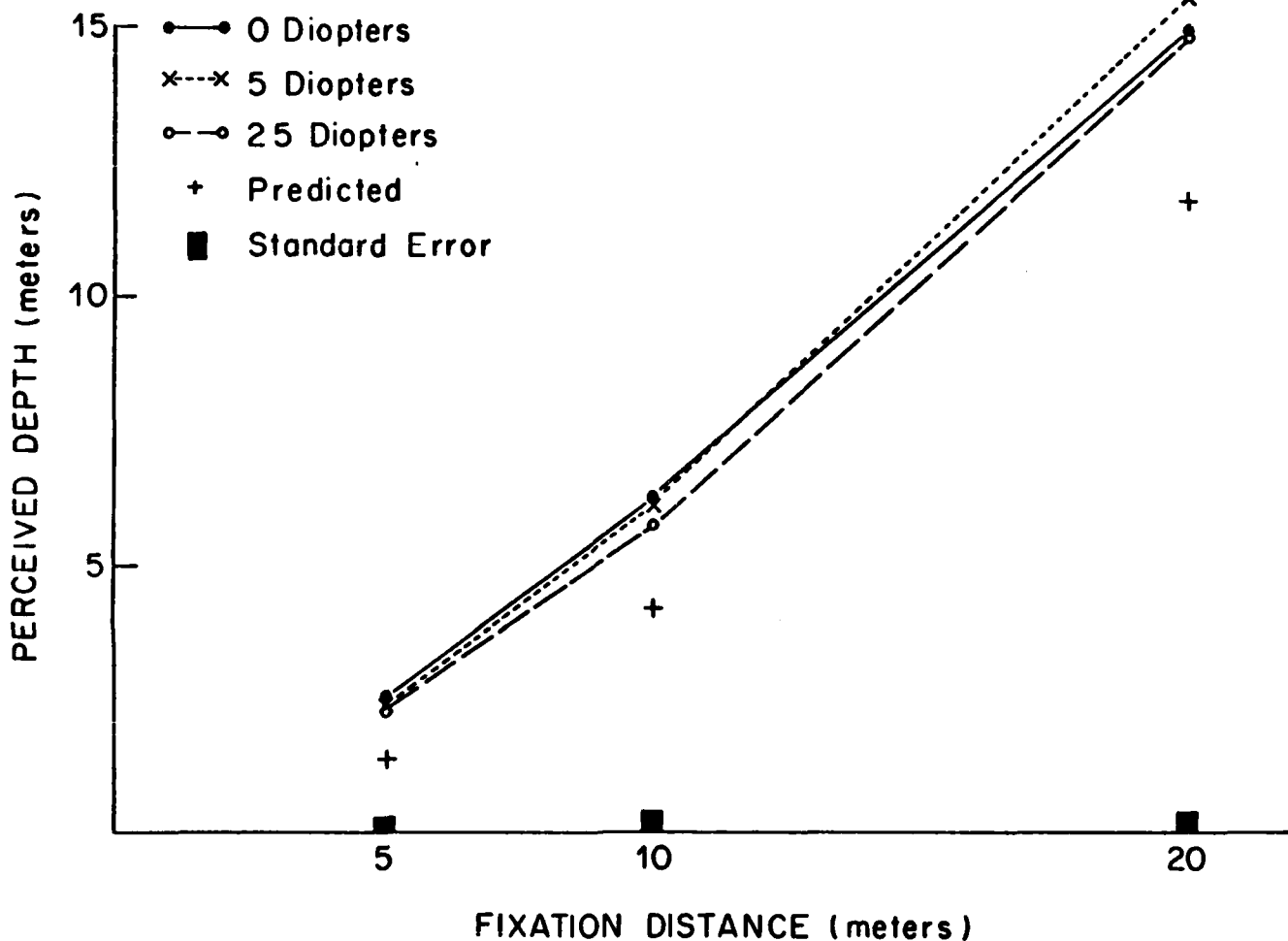
upper left corner of each graph. Each data point represents the mean for all three observers (eight judgments per observer). The unconnected crosses below each set of data points indicate the perceived depth predicted for each fixation distance by the geometry of retinal disparity. The small histogram-like bars along the bottom of the graph give the largest standard error for any observer and for any convergence at the fixation distance specified.

DISCUSSION

The similarity of the results from the three measurement techniques as revealed by Figure 7 is in agreement with previous work (Cormack, 1982b). These findings support the conclusion that the three approaches are all measuring the same thing, i.e., depth perceived in the afterimage. It can be noted in Figure 7 that the foot-estimate technique quite consistently gives smaller depth values than the other two approaches. It is not immediately apparent why this should be the case. Since there is a consistent tendency to overestimate the depth in afterimages with crossed disparity (Cormack, 1982a), the foot-estimate technique gives data in slightly better agreement with predictions based on the geometry of retinal disparity. The present study also found a tendency for observers to overestimate depth. All the data points in Figures 8, 9, and 10 are higher than the predicted values.

Attention to Figures 8, 9, and 10 reveals that, under the conditions of this study, there is little if any consistent effect of convergence on perceived depth in stereoscopic afterimages. It is true that the 25 diopter convergence condition consistently gave the smallest depth measures. On the

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other hand, the 5 diopter condition often gave the largest depth values.
Even the smallest values obtained with the 25 diopter prism are larger than
the depths predicted for normal viewing conditions. Furthermore, there is
absolutely no overlap among the 5, 10, and 20 meter fixation distance re-
sults. This means that in no case did forced convergence trigger a rescal-
ing of disparity sufficient to rival the effects of the changes in fixation
distance.

This point needs further consideration. With 5 diopter prisms, if the
eyes are directed at a target at infinity (say, a star), they will be con-
verged as they would if, without prisms, they were directed at a target 1.3
meters away. When fixating a target 5 meters away, the eyes will be con-
verged as if the target were only 1.03 meters away. If retinal disparity
were rescaled solely on the basis of convergence, then the predicted depth
in the afterimage used in the present study would be less than 15 centimeters,
even when the observer fixates the 20 meter fixation target! With 25 diopter
prisms, the forced convergence is even greater. While fixating a star, the
convergence will be as though it were at 26 centimeters (i.e., a close read-
ing distance). With the target at 5 meters, the convergence will be at less
than 25 centimeters. At this distance, the predicted depth is about one half
a centimeter (i.e., less than the depth in the inducing stimulus).

The forcing of convergence through the use of prisms clearly did not
trigger a rescaling of retinal disparity to the extent suggested by the
above analysis. It is questionable whether any rescaling was triggered.
The conclusion is inescapable that under the conditions used in the present
experiment, convergence alone does not mediate stereoscopic depth constancy.

Several points should be emphasized with reference to this conclusion.
First, remember that the hallway in which the data were collected was rich

in depth cues. Illumination in the hall was sufficient to make these cues easily observable. Observers were free to move their heads and thus obtain motion parallax information. The observers were familiar with the hallway and the fixation target. The walls were painted cement blocks, providing observable texture. There were several doors and ceiling light fixtures. An illuminated "exit" sign protruded into the hallway.

All the observers noted that donning the prisms did not make the fixation distance appear shorter. In fact, the observers made foot-estimate judgments about the apparent distance to the fixation target from the 20 meter distance, with and without forced convergence. There were no consistent differences among the conditions, testifying to the fact that the prisms did not change apparent fixation distance.

These considerations make it clear that there were many sources of information which could be used by the visual system to rescale retinal disparity and preserve depth constancy. It is also important to note that, in the absence of other distance information, convergence might affect the scaling of retinal disparity. Since this might be the case, it would be worthwhile to study the effect of convergence on apparent depth in stereoscopic afterimages under reduced cue conditions. Nevertheless, the results of the present study demonstrate unequivocably that, under normal viewing conditions, convergence plays a minor role in stereoscopic depth constancy.

APPENDIX

DETERMINATION OF DEPTH INTERVAL

GIVEN FIXATION DISTANCE AND RETINAL DISPARITY

Figure Al depicts two objects at different distances from the two eyes.
Both objects are in the midline plane. The fixation distance divided by
half the interpupillary distance gives the tangent of angle b. The arc
tangent of this value gives angle b.

$$b=ATN(D/.5P)$$

Angle c is equal to half the retinal disparity (R). Subtracting angle c
from angle b gives us angle a.

$$a=ATN(D/.5P)-.5R$$

The tangent of angle a is the ratio of the distance of the near object to
one half the interpupillary distance.

$$E/.5P=TAN(ATN(D/.5P)-.5R)$$

Multiplying this tangent by one half the interpupillary distance gives the
distance to the near object (E).

$$E=.5P(TAN(ATN(D/.5P)-.5R))$$

Finally, subtracting E from D gives d, the depth interval.
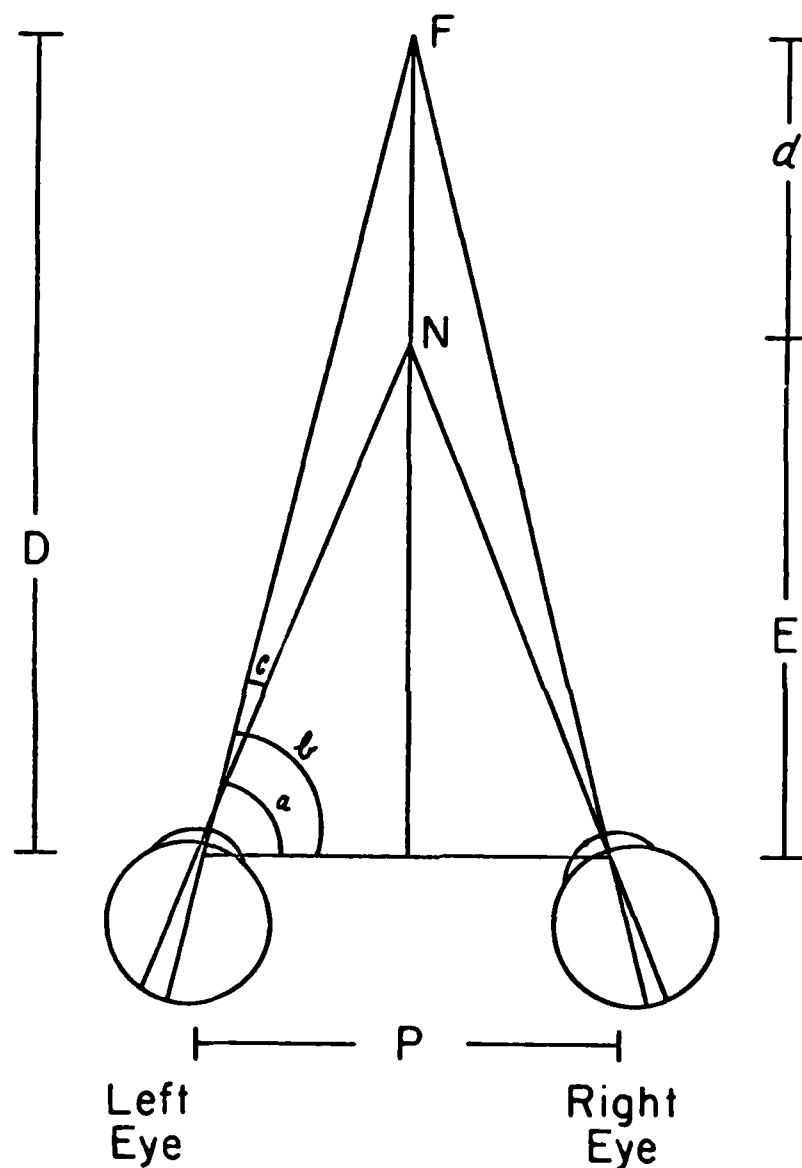
$$d=D-(.5P(TAN(ATN(D/.5P)-.5R)))$$

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Figure A1. Depiction of geometry used to derive the relationship among depth, fixation distance, and retinal disparity. F – far target; N – near target; D – fixation distance; E – distance to near target; d – depth interval; P – interpupillary distance. Note that angle "c" is equal to one half the retinal disparity.

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